

Die Wear Profile Investigation in Hot Forging

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Abstract—In this study, the wear profile on the die surface during the hot forging operation for an axisymmetric cross-section is examined. In the field of metal forming, reliable estimations of die wear and its distribution on the die surfaces can greatly influence the life of the forging dies. The amount of wear is calculated for two wear models by implementing a rigid thermo-viscoplastic finite element analysis into the metal forming process. The first model consists of the classical model which proposes that the amount of the wear is proportional to the die pressure and sliding length. Whereas, the second model assumes that the wear is proportional to the energy dissipated on the tool/workpiece contact interface. Finally, the influence of the friction on the amount of die wear and the material flow is discussed. From this study, it is found that these models are in agreement with each other. They are also consistent with the prediction of the location of heavily worn areas on the die surface. It was also concluded that the increase of friction coefficient does not enhance the die wear in general.

Index Terms—Wear, friction, hot forging, rigid thermo-viscoplastic finite element.

I. INTRODUCTION

In high-temperature metal forming processes, die life has an important role on the productivity and the quality of the finished products. According to an investigation carried out by Stahlberg and Hallstrom [1], more than 70% of tool replacements are due to premature die wear. Another 25% are due to mechanical fatigue, and the remaining 5% are due to plastic deformation and thermal-mechanical fatigue. Therefore, the die wear is the dominating tool failure factor for the forging tool replacement during the mass-production. Numerous studies have been performed both experimentally [2] and numerically for prediction of die wear. In this paper two empirical wear models are used to estimate the die wear based on the finite-element analyses. The first model proposed by Archard [3], is based on the assumption that wear is proportional to the contact pressure and the sliding length. The aim of this study is to determine the die wear distribution during hot forging operation of an axisymmetric cross-sectioned forging using above methods. The finite element simulation is used to calculate the amount of die wear. The influence of friction on the die wear and the material flow is discussed for this forging component. All simulations in this study are conducted to obtain field solutions such as metal flow, contact stress and pressure using the commercial FE code ABAQUS. The sliding length and contact stress are used to calculate the die wear. A FORTRAN user subroutine has been implemented to estimate the die wear automatically.

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II. WEAR STUDY

Prediction of the die wear is an essential task during the die design process. In fact, in the optimum die geometry design procedure, the choices of die material and lubricant type have a great influence on the die wear condition. The result of excessive wear can initiate unsuccessful die cavity filling. It can also cause forging defects on the final products which are not within the specified dimensional tolerances. An optimum design should prevent premature die wear and excessive worn areas of the die surface. Critically worn areas of the die surface can usually be referred by changing the die design and geometry, thermal and heat treatment of the die surface, die material selection and lubricant type.

In hot forging, the abrasive particles are the main cause of die wear which is developed by the mechanical friction between die surface and workpiece. These particles can damage the die surface progressively during each die stroke. The abrasive particles may be hard oxides or scales, external-contaminating particles or other hard carbides dislodged from the die surface. Abrasive wear results in removal of die material from the surface and its amount depends on numerous parameters such as temperature, surface roughness, sliding length, relative velocity, material, contact pressure and lubrication. Due to its complicated nature, it is difficult to formulate relationship between parameters and the amount of die wear. Several works have been reported in the literature [2] that attempt to characterize and model the wear of die in hot forging. Some of which are based on the process variables like forging cross-section area, component weight and forging energy while others have taken a more fundamental approaches. In the present paper two well-established wear models are used. Model.1, proposed by Archard [3] is based on the assumption that wear is proportional to the contact pressure and sliding length. This model is presented in the following formula

$$dV = k \frac{dp \cdot dL}{H} \quad (1)$$

Where: dV is the wear volume, dp is the contact load, dL is the sliding length and H is the tool local hardness and k is an experimental constant.

In model.2, it is assumed that wear is dependent on the dissipated energy on the tool/workpiece interface that can be called "friction work". The equations associated with this hypothesis are presented below.

$$\begin{aligned} dV &= C \cdot dW \\ dW &= \tau \cdot dA \cdot dL \end{aligned} \quad (2)$$

Where: dL is sliding length of the material along the tool surface under influence of shear stress τ and dA is contact area.

According to the result of investigation, including

experimental observation [1], model.2 points out the critical areas of the die more distinctively than model 1.

III. NUMERICAL DETERMINATION OF THE WEAR PROFILE

Using the recent advances in finite element method and computing power of modern computers, it is now possible to use fundamental material properties and process variables derived from FE to model wear more universally. Estimation of wear using FE simulation requires that appropriate wear models to be available in discretized form. In Archard model dV, dp and dL in equation 1 can be expressed as follows

$$dV = dZ \cdot dA, \quad dp = d\sigma_n \cdot dA, \quad dL = u \cdot dt \quad (3)$$

Here, dZ is the depth of wear, u is the sliding relative velocity and dt is the sliding time. By substituting equation 3 into equation 1 and dividing both sides by dA , equation 1 can be rewritten as such that r and t represent position and time parameters, respectively

$$dZ = k \frac{\sigma_n(r, t) u(r, t)}{H} \cdot dt \quad (4)$$

The values of the wear parameters, σ_n and u can be obtained from rigid-thermoviscoplastic finite element simulation and substituting them into equation 4, allows for evaluation of the wear of each point of the die surface at each time step of the simulation. Based on total time duration of the forming process, the wear at each point can be calculated through a time integral as

$$Z = k \sum_{i=1}^M \frac{\sigma_n(r, t) u(r, t)}{H} \cdot \Delta t \quad (5)$$

Here, Δt is the time step and M is the total number of time steps. The accumulated wear for each point of the die surface according to model.2 can be represented in discretized form as follow:

$$Z = C \sum_{i=1}^M \tau(r, t) u(r, t) \Delta t \quad (6)$$

According to discretized form of these models, for each model an index coefficient

can be defined such that it can represent the wear in each k th point of the die. For example in model 1, if H is assumed to be constant then this index can be represented as follow

$$\eta^k = \sum_{i=1}^M \sigma_n^k(r, t) u^k(r, t) \Delta t \quad (7)$$

And for model 2

$$\lambda^k = \sum_{i=1}^M \tau^k(r, t) u^k(r, t) \Delta t \quad (8)$$

For each point on the die surface, these indexes are calculated and the critical wear areas of the die surface can be recognized when they are plotted versus radial coordinate of the die surface. To calculate the above equations, the normal

stress, the shear stress and the sliding length at the workpiece/die interface are needed. In order to calculate the normal stress, the shear stress and the sliding length at the workpiece/die interface, the contact data from the boundary nodes of the workpiece is projected to the surface of the lower and upper die cavities. Firstly, for each time step of the simulation, the boundary nodes of the workpiece (that are in contact with the die surfaces) are sorted by ascending order based on the radial coordinate values. Secondly, location of each die node is determined and two surrounding workpiece boundary nodes are selected. Finally, the wear parameters of each point on the die surface are calculated using the Euler interpolation technique. For example, as shown in figure 1, the local shear stress acting on the die cavity surface can be determined as follows

$$\tau_i = \tau_j + \frac{r_j}{r_j + r_{j+1}} (\tau_{j+1} - \tau_j) \quad (9)$$

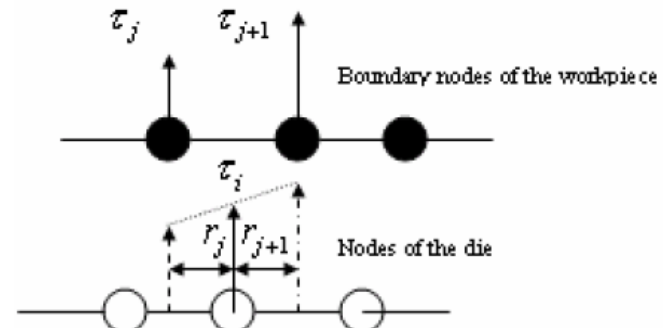


Figure 1: Schematic diagram representing the project of shear stresses between the workpiece and die surfaces [5].

In order to determine the sliding length during each time step, the instantaneous hodograph is drawn in which the sliding length becomes clear (see figure 2).

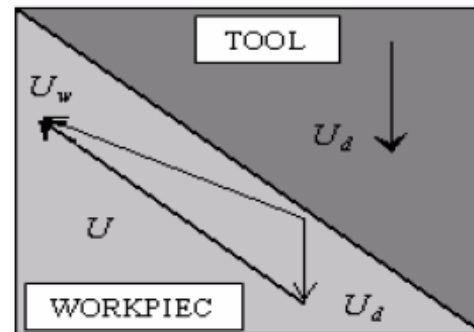


Figure 2: Hodograph for evaluating the sliding length: $d u$ is displacement of die and $w u$ is displacement of boundary nodes of workpiece [1].

IV. THE MODEL VALIDATION

An axisymmetric cross-section flange forging component as a case study has been referred in reference 2 is used here to perform model validation. Figure 3 illustrates the result of the study carried out in reference 2. As indicated in figure 3, most worn zones from experimental observations are evident in final step and have been highlighted by a number of arrows in this figure.

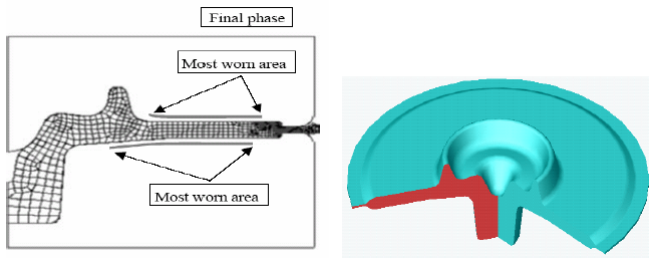


Figure 3: Geometry of the flange and the most worn areas [2].

Distributions of wear (index λ) on the upper and lower dies, using model 2 are shown in figure 4. The locations of critical areas that can be seen in this figure have a good agreement with experimental results shown in figure 3.

V. THE CASE STUDY

The case study refers to the industrial hot forging of a gear blank in a closed die forging process. The final step of forging is accomplished using a hydraulic press. All data for the FE simulation comes from industry. The initial forging parameters consist of die and billet geometry, flow stress of billet (DIN C43), working temperature (1220oC for the billet and 300oC for the dies) and velocity of press (0.1 m/sec). The FE model is axisymmetric and the simulation type is non isothermal. The friction at model is presented in equation 10.

$$\begin{aligned} \tau &= \mu \cdot p & \tau < \tau_{\max} \\ \tau_{\max} &= \frac{m \sigma_e}{\sqrt{3}} \end{aligned} \quad (10)$$

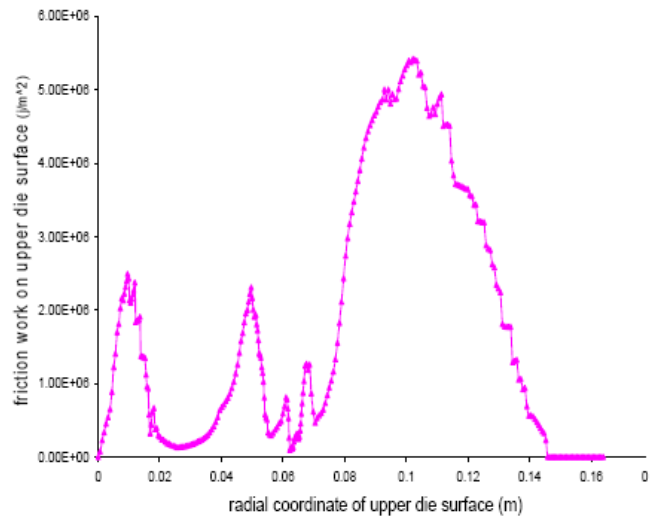
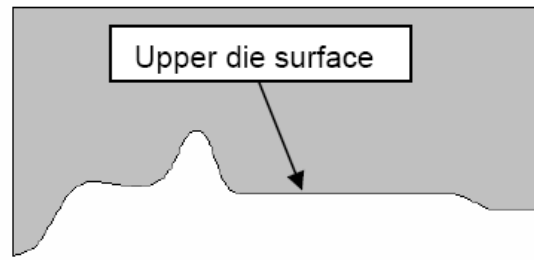
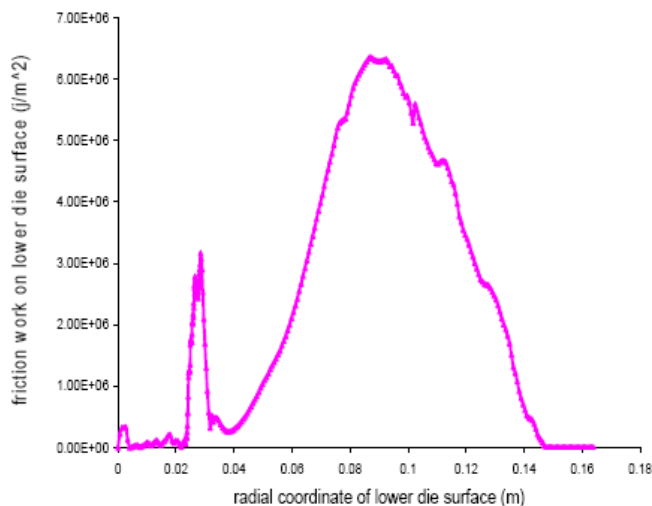
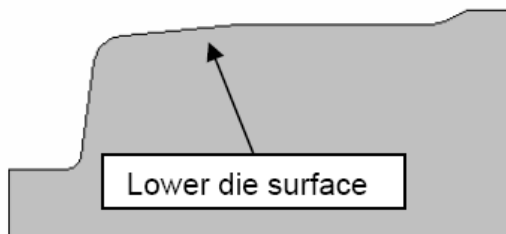


Figure 4: Distributions of wear (index λ) on the upper and lower dies.

According to equation 10 the shear stress τ , acting on the tool/workpiece interface at low pressures is only influenced by tool pressure p and friction coefficient μ . However, at high pressures, it is merely dependent on the shear friction factor m and the flow stress σ_e of the material.

In order to calculate wear index, the simulation results are needed in terms of material flow, pressure and shear stress at the interface between die and workpiece. These results are then incorporated into the wear calculation subroutine. Figure 5 illustrates the material flow during the simulation.

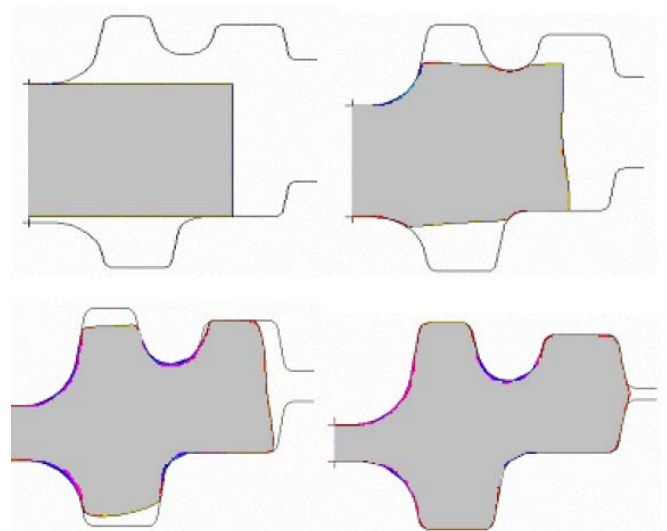


Figure 5: Metal flow patterns during simulation with $m = 0.1$.

Distributions of wear (index λ) on the upper and lower dies, using model 2 and with different friction factors are shown in figure 6. According to this figure, the amount of wear in the die corners is very low. This is due to trapping of material in these areas and minimum sliding effect. On the other hand, the amount of wear seems to be comparably high in the convex fillets especially for those which are near the deep ribs and the centre of the die. By analysing the results of these simulations for different friction factors, it can be inferred that the locations of most worn areas remain the same and is not dependent on the friction factor. In addition, in some areas the amount of wear is not directly dependent on friction factor.

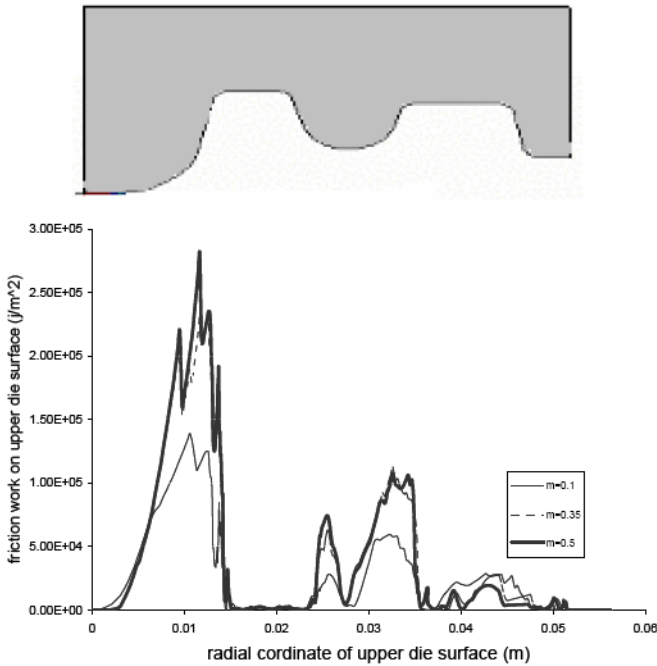


Figure 6: Distribution of upper die wear with different friction factors.

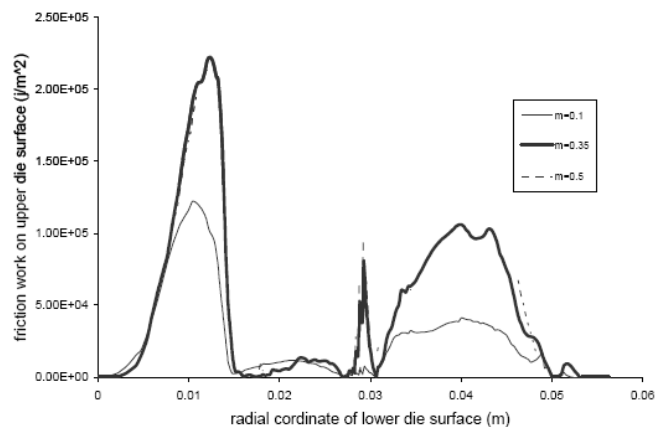


Figure 7: Distribution of lower die wear with different friction factors.

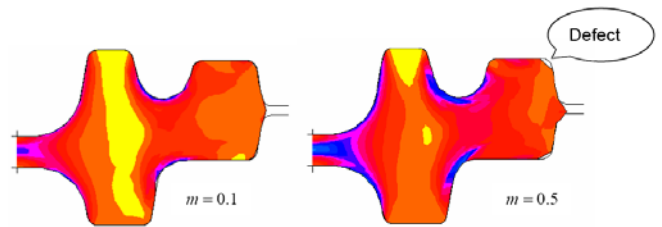


Figure 8: Formation a defect with increasing of friction factor.

The reason for fluctuation of die wear with respect friction factor is that the material flow and the velocity fields are affected by it. For example, in this forging component an increase in friction factor will result in a change on the material flow and an increase on the probability of defect formation (See figure 8) In figure 9 two wear models were compared to determine the upper die wear. According to this figure, these two models have a good agreement in detecting the most worn areas.

VI. CONCLUSION

The numerical determination of die wear profile in hot forging operation was presented in this paper. The influence of the friction on the amount of die wear and the material flow were discussed. It was seen that the variation of friction factor/coefficient doesn't have any effect on amount of die wear at the worn areas. From this study, it is found that these models are in agreement with each other. They are also consistent with the prediction of the location of heavily worn areas on the die surface. It was also concluded that the increase of friction coefficient does not enhance the die wear profile in general.

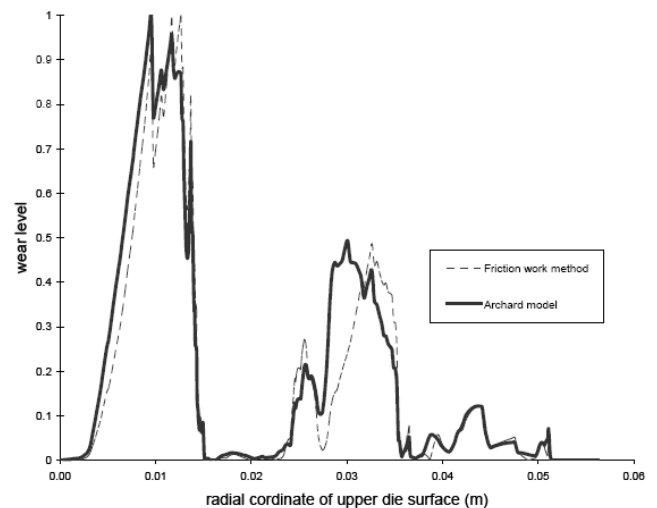


Figure 9: Comparison between Archard model and friction work method in discernment of the most worn areas.

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